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Fitts' law revisited: The relationship between cursor size and target size in manual aiming.

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FITTS' LAW REVISITED:

THE RELATIONSHIP BETWEEN

CURSOR SIZE AND TARGET SIZE IN MANUAL AIMING

by

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ABSTRACT

Manual aiming research usually requires participants to aim a cursor to larger sized targets. To date, there are few instances where participants use an aiming apparatus larger than the target being aimed to, despite similar situations that occur throughout daily living. Such examples are manually pressing the buttons on a phone or placing a large pot over a small element on a stove. Researchers describe this relationship as "Tolerance", the difference between the aiming apparatus and the target. As this is an uncommon approach, a universal definition does not exist. The present study set out to address this issue and to try to come to a better understanding about the target – cursor relationship.

Participants were required to aim a 9mm cursor to five different sized targets, 3, 6, 9, and 12mm. Participants aimed to these targets in two different visual conditions. A full vision condition, where participants had vision of the cursor and target throughout the entire movement, and a partial vision condition, where vision was available throughout the movement until termination, where vision was occluded for 30% of the targets. Kinematic, temporal and correction data was collected to determine the control processes underlying this relationship and to better understand tolerance.

No effects were found due to vision, indicating that eliminating only terminal vision provides enough visual feedback to perform the movement successfully. Generally, movement time decreased as target size increased. However, the smallest target produced a fast time in comparison to other targets. This was a negative tolerance condition and the fast movement time was attributed to the target appearing to become like the cursor. Results also suggest that the initial phase of the movements were

preprogrammed as predicted by Woodworth (1899). The deceleration data suggest that on-line, concurrent vision was used during the final stages of the movement for error correction.

The current study demonstrates that the participants take tolerance into account when planning and executing their movements. Support for these data are found in a recalculation of Fitts' (1954-Experiment 2) data. When tolerance is computed according to the current equation a similar movement time pattern is revealed.

DEDICATION

This master's thesis is dedicated to my advisor, mentor and friend, Patti Weir. It has been her dedication to her students, profession, and science that has inspired me to pursue graduate studies. Patti's relentless support, knowledge and patience were invaluable. She is responsible for the spark that caused my interest in the area of Motor Control. Thank you for believing in me; thank you for the enormous amount of effort you bestowed into this research, without you this work would not have been possible.

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Introduction

Everyday humans perform activities that require aiming to an object for manipulation. Such actions take place without any thought to how they have been carried out. What are the underlying controls that allow us to perform such activities accurately and at various speeds? Visual and kinesthetic awareness are dominant control systems in these tasks as shown by Carlton, 1981a; Elliott & Calvert, 1990; Elliott, Carson, Goodman, & Chua, 1991. However, there are many movements we perform where vision is occluded at various stages of the movement. Everyday examples of this include reaching into a dark cupboard or bag, a finger covering the buttons on a calculator or placing a large stockpot over a smaller stove element. An important question is when does vision become critical to the results of our movements and how does the motor system deal with the inconvenience of the absence of visual monitoring?

The proposed research has been developed to address: 1. the influence of vision on manual aiming and 2. the relationship between target size and cursor size in manual aiming.

Speed Accuracy Relationship

The relationship between movement speed and accuracy has been of interest for over one hundred years. In 1899, Woodworth made the first attempt to study this relationship scientifically while setting the tone for future work on information processing. His research involved subjects drawing lines on sheets of paper with a pencil as the paper rolled at a constant speed. Subjects attempted to aim for a fixed target or to match the spatial endpoint of the previous movement. Subjects performed this task under different conditions: with their right and left hand, with eyes open and closed at different instances during the movement, and varying their speed to the beat of a metronome.

Woodworth predicted more accurate movements when subjects had vision compared to movements made without vision as long as there was enough time to process the visual information. This expectation was based on Woodworth's assumptions about the control of aimed movements. From this work he identified two phases of an aiming movement: 1) the initial adjustment phase where the hand moved towards the target, and 2) the current control phase that involved the correction of errors to provide high spatial accuracy. While spatial error corrections could be mediated by other sensory information sources, Woodworth felt that vision was the strongest sensory modality for error corrections in an aiming movement.

He was also interested in how movement speed affects accuracy, and through this research, realized that spatial accuracy partially relied on visual feedback. Knowing this, Woodworth hypothesized that movements of short duration would not benefit from visual feedback while movements of longer duration would. Woodworth found movements with the shortest duration were accurate as movements with or without vision. This suggests that the movements were made so quickly there was not enough time to process any visual information. Generally, he found that as movement speed increased accuracy decreased. This phenomenon is known as the speed-accuracy trade-off, a term coined by Paul Fitts in 1954.

Fitts (1954) presented a systematic analysis of the speed-accuracy relationship through a formal mathematical equation, which is known today as Fitts' law. The Fitts' experiment involved a subject tapping a hand held stylus alternately between two targets in a horizontal plane. The width (W) of the two targets and the amplitude (A) between them could be manipulated across conditions to produce different combinations of A and W. The number of taps within a 20s period was recorded as the subject's score.

Fitts found the relationship between amplitude (A), width (W), and the resulting average movement time ($\overline{MT}$) was represented by the following equation:

$$\overline{MT} = a + b[\text{Log}_2 (2A/W)] \qquad (1)$$

The average movement time is linearly related to the quantity of $\text{Log}_2(2A/W)$. Therefore, if average MT were to be plotted against $\text{Log}_2(2A/W)$ on a graph, the result should be linear.

According to Fitts, difficulty of a movement is related to the distance the limb must move and the width of the target. Therefore, Fitts termed the value of $\text{Log}_2(2A/W)$ the "index of difficulty" (ID). The ID reflects the amount of time required for each movement. ID is measured in bits, where one bit is the amount of information required to reduce the original uncertainty by half (Schmidt, 1988)

The original interpretation of Fitts' law was that the human motor system is an information processor. Thus, increasing amplitude or decreasing target width makes a movement more difficult, because more information needs to be processed to generate an accurate movement that will hit the target. The amount of information individuals can process at one time is limited, therefore individuals choose to increase movement time for difficult movements to ensure accuracy (Schmidt, 1988).

Since Woodworth's 1899 study, an enormous amount of research in the area of visual processing and visual feedback has been conducted. Much of this research uses the Fitts' law paradigm as the foundation of the experiments. Fitts' law is quite versatile and robust and holds within many contexts: reaching and grasping (Carson, Goodman, Chua, & Elliott, 1993; Roy, Weir, Desjardins-Denault, & Winchester, 1999) and discrete aiming movements (Carlton, 1994;Yao & Fischman, 1999), movements in the vertical (Heath, Hodges, Chua, & Elliott, 1998) and diagonal planes (Whisenand & Emurian, 1999) as well as movements by the hands or feet (Drury, 1975; Hoffman, 1991). Researchers often modify Fitts' paradigm by employing conditions of no vision, partial vision, perturbed vision, or changing the direction of the movement. Most researchers find that full vision conditions result in superior performance, compared to any other type of vision condition. The superior performance is attributed to the modifications made due to the presence of visual feedback about the movement (Carlton, 1992), and the time to process the feedback. To date, much of this research has involved aiming to a target where the object used to contact the target is smaller than the target itself (see Table 1).

Table 1. Sample of aiming studies indicating target versus cursor size.

ARTICLE	POINTING OBJECT	TARGET SIZES	AMPLITUDE
Bryden & Roy, 1999	pegs: 1.25, 1.09, 0.9375, 0.781 cm	1.25cm	20.8cm
Carlton, 1981a	stylus[1]	1.27cm	32, 64cm
Goggin & Meeuwsen, 1992	stylus	0.5, 1.0, 2.0cm	10, 20cm
Heath et al., 1998	0.5 cm cursor	0.5cm, 1.5cm, 4cm	13cm
Heath, Roy, Weir, 1999	0.4 cm cursor	0.5cm, 1.2cm, 3.1cm	17cm
Klapp & Greim, 1979	stylus (9.7 g)	2, 4, 8, 16, 32, 64mm	2mm
Ricker, Elliott, Lyons, Gauldie, Chua, & Byblow, 1999	stylus	12.5, 25, 50mm	21, 42cm
Spijkers & Spellerberg, 1995	stylus	Width=5mm, Height=100mm	16.75cm
Teeken, Adam, Paas, van Boxtel, Houx, Jolles, 1996	stylus	4, 12, 32mm	80mm
Whisenand & Emmurian, 1999	Crosshair 3 mm x 3 mm	4, 8, 16mm	20, 40, 80, 160mm
Zelaznik, Mone, McCabe, Thaman, 1988	stylus	5cm line (0.5mm thick)	15, 20, 30cm
Zelaznik, Schmidt, Gielen, 1986	stylus	5cm line (0.5mm thick)	20, 25cm

Tolerance

As previously stated, there are few instances where researchers adopt an experimental design requiring participants to aim to a target smaller than the aiming apparatus. When such instances do exist the relationship between the target and the cursor can be described by tolerance. As originally defined, tolerance is the difference

[1] Estimating that the tip of the stylus used in most studies would be equivalent to the tip of a pen. It would be approximately 2mm.

between the target and the cursor [Target – Cursor] (Fitts, 1954). Values can be positive, negative, or an absolute value of the tolerance can be used. There is no consensus among researchers as to a formal definition of tolerance. Researchers adopt the basic concept of tolerance, the idea of the relationship between the aiming apparatus and the object/target being aimed to; however, how they implement tolerance and their method of analysis differs.

Fitts used tolerance in his seminal 1954 paper discussing the logarithmic relationship between speed and accuracy. One experiment involved a disc transfer task, where subjects were required to transfer round plastic washers from one pin to another. Amplitude and tolerance were varied among trials and tolerance was described as the difference in inches between the diameter of the pin and the diameter of the hole in the washers. The greater the difference, the easier the task was. Participants decreased movement time as tolerance became less stringent (larger) and as amplitude decreased. In all cases tolerance was a positive value ranging from 0.0625 (most difficult) to 0.5 (least difficult).

A second experiment focusing on tolerance employed a pin transfer task (Fitts, 1954). Participants were required to transfer pins from one set of holes to another. There were four sizes of pins that participants transferred (1/4, 1/8, 1/16, and 1/32 inches in diameter) across five different amplitudes ranging from 1 to 16 inches. Each set of pins was placed in a set of holes with a diameter twice the size of the pins. Tolerance was determined by the difference in inches between the diameter of the pins and the diameter of the hole into which they were inserted. Tolerance values ranged from 0.03125 to 0.25 inches with every tolerance value being positive. Falling in line with the previous experiment, movement time decreased as the tolerance became less stringent (larger tolerance value) and the amplitude decreased.

Drury, in 1975, examined the role of Fitts' law when designing foot-pedals for automobiles. Subjects performed a reciprocal foot-tapping test. A successful "hit" on the target (a wooden block resembling a foot-pedal) was determined by any part of the sole of the subject's shoe landing on the top of the target. Drury's experiment tested whether Fitts' equation (Equation 1) produced a linear result, as foot movements are analogous to hand movements. Only when the average sole width of the subjects' shoes was added to the target width did the equation hold. Drury used an effective target width (tolerance), which is the sum of the actual target width and the width of the shoe. Modifying the index of difficulty, by increasing target width, reduces the ID and therefore accounts for the decreased movement time. Drury felt that without adding the width of the shoe to the target, results were not a good representation of what was actually occurring.

Similarly, Drury and Hoffmann (1992) assumed that subjects used the full width of an aiming probe as additional allowable tolerance when making an aiming movement. According to Drury and Hoffmann (1992), when aiming to a single target the effective target size is close to the sum of the target and finger width, and therefore determines the effective target width. Their study had participants hitting five different sized keys with one of four different sized probes or their index finger. Results indicated that as probe size increased MT decreased, as target size increased MT decreased, and as target and probe size increased together, MT decreased.

Another use of the term "effective tolerance width" was proposed by Schmidt, Zelaznik, Hawkins, Frank, & Quinn (1979). Here, effective target width is "the size of the target area that the performer actually uses in a series of aiming movements, calculated as variable error of the movement endpoints" (Schmidt, 1988, pp. 298). It is considered the variability in distance moved, and is a "measure of accuracy of the response in achieving the target area" (Schmidt et al., 1979, pp. 419). The effective target width is directly proportional to the variability in time after peak velocity and is directly proportional to the variability in the impulse for acceleration. The group proposed that when subjects are performing aiming movements to a target they develop an effective target size based on a particular amplitude and movement time. These effective target sizes are based on subjects' variability at the end of the movement. Applying this notion to the idea of tolerance indicates that participants, in a sense, develop a new target size based on the difficulty of the task requirements and their variability of the movement endpoints. Schmidt et al. (1979) allowed their participants a 10% error rate in the aiming movements, being less stringent than Fitts (1954). The participants in the 1979 study were required to aim to a target under specific goal movement times. Results indicated that the relationship between movement time and effective target width did not hold for longer movement times (200 to 500ms). This finding was attributed to Keele and Posner's (1968) results, which demonstrated that with longer movement times, participants have enough time to correct any error due to impulse. Therefore, Schmidt et al.'s (1979) experimental design allowed enough time for correction within the goal movement times. Schmidt et al. (1979) found an increase in variability, therefore a need for an effective target width, when the movement time goal was decreased (140 to 200ms).

Another use of tolerance implemented by researchers is in the form of an inverted Fitts' paradigm, where participants aim a probe or cursor, which is larger than the target they are aiming to. Researchers add the aiming apparatus, for example the width of a shoe (Drury, 1975) to the width of the target to determine the 'effective' target tolerance (Hoffmann, 1995). Hoffmann and Sheikh (1991) note the importance of effective target tolerance when estimating the movement times based on the index of difficulty. With a larger aiming apparatus, and therefore a larger effective target size, the index of difficulty decreases. With a decreased index of difficulty, movements that should have been visually controlled are more ballistic in nature. Hoffmann (1995) found that as probe size increased MT decreased, as target width increased MT decreased, and as both target probe size increased together MT decreased. These results suggest that an effective target tolerance was used.

Comparing the different uses of tolerance it is clear that Fitts' use is more stringent compared to that of Drury and Hoffmann (1992) and Hoffman (1995). Fitts only allowed the difference between the target and cursor for endpoint variability, with a 5% error rate. Whereas, Drury and Hoffmann (1992) did not allow any errors by subjects, they added the cursor and probe to the target as an effective target tolerance, they accepted any part of the cursor hitting the target as a successful movement making the task less difficult, and they make no mention of an imposed error rate. With Drury and Hoffmann's (1992) use of tolerance, movements do become much easier as there is more freedom for the subject to have a successful movement. Hoffmann (1995) allows for a 10% error rate, yet again there is a large allowable margin of error compared to Fitts (1954).

Given the above review, the current study adopts Fitts' original definition of tolerance, using a task similar to Hoffmann (1995) where the cursor is both smaller and larger than the target.

Vision and Corrective Movements

While Fitts' experiments and analysis did not focus on visual feedback processing or a manipulation of vision, other researchers (Crossman & Goodeve, 1963/1983; Keele, 1968) have examined the role that vision plays in the speed-accuracy relationship. These researchers believe that Fitts' law could be presented from an iterative-correction model. This model purports that aiming movements are made up of many submovements that rely on feedback. The feedback control can be either visual or kinesthetic, but Keele (1968) suggested that spatial accuracy was a function of visual feedback because spatial accuracy decreases when vision is occluded.

Similar to Woodworth (1899), other researchers (Crossman & Goodeve, 1963/1983; Keele, 1968) theorized that aiming movements were made up of at least two discrete submovements that rely on visual feedback. Each movement is thought to have a defined start and end point, take a constant time to complete, and travel a constant portion of the distance remaining to the center of the target. The first of the submovements is spent "homing" in on the target and the second (or subsequent) submovements are spent making corrections to obtain an accurate spatial endpoint. This suggests that the first submovement is nearly completed without the aid of visual feedback.

The iterative-corrections model quantitatively supports Fitts' law. This is accounted by the fact that for a specified target region, the number of submovements that occur increases as in a logarithmic fashion due to the relationship of A/W (Meyer, Abrams, Kornblum, Wright, and Smith, 1988). If each submovement takes a constant amount of time, as the model assumes, then the total movement time, made of two or more submovements, would be an approximately logarithmic function of A/W, producing Equation 1.

Unfortunately, there are limitations that exist with the iterative-corrections model. Although the model is useful in quantifying Fitts' law, "it cannot deal with other observed characteristics of rapid aimed movements, such as the duration of primary (initial) submovements, the spatial variability of submovement endpoints, the relative frequency of higher order (e.g., secondary) corrective submovements, the relative frequency of errors (target misses), and the effects of feedback deprivation" (Meyer et al., 1988, p. 343). Any motor performance theory must be able to explain these various phenomena.

In 1988, Meyer et al. provided evidence to support the stochastic optimized-submovement model as an explanation for the control of aiming movements, where feedback-based error corrections are in the form of discrete corrections to the movement trajectory. Keele (1981) defined these corrective movements as impulses responding to and reducing visual error. A key feature of this model is that it represents the movement-production process as a compromise between the duration of primary and secondary submovements (Meyer et al., 1988). The compromise depends on assumptions concerning neuromotor noise and the spatial variability of submovement endpoints. The authors proposed this theory as an improvement over the iterative correction model. This model applies specifically to time-minimization tasks, for example, a Fitts paradigm (Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

There are six basic assumptions involved in the stochastic optimized-submovement model that help to explain the theory on which this model is based. The first involves neuromotor noise. According to this assumption, whenever rapid aimed movements are produced noise is assumed to exist in the neuromotor system. Neuromotor noise manifests itself as movement variability and is believed to exist as subjects are unable to produce the same result after identical trials. This noise causes random movement time values to occur when subjects are repeatedly aiming to a target of the same size and amplitude, therefore subjects are unable to produce identical movements repeatedly across a series of trials (Meyer et al., 1988). The source of noise is not known and for present purposes it is not important to identify its underlying mechanisms. The second assumption concerns the number of submovements involved in an aimed movement. It is assumed that one or two component submovements make up the rapid spatially constrained movement towards a target region, despite target width or distance. The primary submovement is presumably programmed to end on the center of the target. If this movement is successful and ends within the target region, there is no need for more submovements and the movement has terminated. If perturbations due to neuromotor noise occur, the subject may miss the target and execute one or more secondary submovements prepared by visual or kinesthetic feedback. A third assumption posits normal distributions of submovement endpoints. The primary and secondary endpoints are assumed to have normal distributions around the center of the target because of neuromotor noise. This is consistent with Fitts (1954), as he found subjects to overshoot, undershoot, and hit the target with equal frequency.

The standard deviation of submovement endpoints is the basis for assumption four. "The distribution of primary-submovement endpoints is assumed to have a standard deviation…that increases proportionally with the average velocity…of the primary submovements," all related to the neuromotor noise of the system (Meyer et al., 1988, p. 346). Minimization of movement times is the focus for the fifth assumption. The model predicts that the primary and secondary submovements have programmed average velocities to minimize the average total movement time. However, neuromotor noise could compromise such velocities. Meyer, et al. (1988) indicated that time minimization is achieved through a compromise between the mean duration of the primary submovements and the mean duration of the secondary corrective submovements. Such a compromise is needed as primary submovements that occur with very high velocities increase the probability of missing the target. The secondary submovements are required because with an increase in the primary submovement velocity there is as increase in the standard deviation of primary submovements' endpoints. Causing the primary submovement to have a slower velocity, in turn causing the primary submovement to be more accurate generally, resulting in the need for less secondary corrective submovements. Therefore, to minimize the total time, primary submovements should not be very fast or very slow and secondary submovements should not be too frequent or too infrequent. Finally, the sixth assumption is concerned with preparatory processing of information for movement production. According to the stochastic optimized submovement model, movement generation requires certain information to be processed before the movement begins. It is assumed for primary submovements that the necessary information is target width and amplitude, which are processed before the initiation of the primary submovement. A secondary submovement may rely on information about the primary submovement such as target's location and visual or kinesthetic feedback (Meyer et al., 1988).

In 1988, Meyer et al. tested the stochastic optimized submovement model in the absence of concurrent visual feedback while performing a spatially constrained movement. According to this model, with the absence of visual feedback there will be an increase in average total movement times or errors. This falls in line with the model's assumptions concerning secondary submovements. Secondary submovements are performed to overcome deviations due to neuromotor noise. Secondary submovements occur during the actual movement to compensate for any errors. If visual feedback is not available the secondary submovement should suffer, as it will not be able to control movements based on feedback regarding the primary submovement (Meyer et al., 1988). Eliminating visual feedback presumably will increase total movement time and increase the number of errors. Two strategies were proposed to compensate for the reduced visual feedback. The first would be to make primary submovements only by slowing down the movement, with the end result of increasing movement times. Second, subjects may perform a two-component submovement without the use of visual feedback (although possibly relying on kinesthetic feedback). In this case, movement times may be kept to a minimum yet error rates will increase as subjects rely on degraded information. They hypothesize that subjects would most likely use a combination: the two-submovement option while performing movements more slowly to reduce errors. Movements in this situation will be slower than in a full vision condition however, not as slow as they would be if just the primary submovement is implemented. Results will have fewer errors compared to quick movements relying on kinesthetic feedback (Meyer et al., 1988).

Meyer et al.'s 1988 study involved two conditions, a full vision-cursor condition and an invisible-cursor condition. The full vision-cursor condition yielded results that followed the predictions of the stochastic-optimized submovement model. They found that "the average total times, mean primary-submovement durations, standard deviations of primary-submovement endpoints, relative frequencies of secondary submovements, mean secondary-submovement durations, and error rates all increased with target difficulty as the model predicts" (Meyer et al., 1988, p. 364). In the invisible-cursor condition subjects adopted the two-submovement strategy. When subjects did not have vision of the cursor there were no significant increases in the mean primary-submovement durations, the mean secondary durations, or the average total movement times compared to the full vision-cursor condition. Two of the variables, average total movement time and mean secondary submovement durations, decreased while the mean primary-submovement durations stayed the same. This falls in-line with the model as it demonstrates subjects' inclination for time minimization. The relative frequencies of the secondary submovements changed slightly, with relation to the vision condition, when the cursor was occluded error rate increased with the lack of concurrent vision. This indicates that secondary submovements rely on information produced from the primary movements and that they are not programmed before movement is initiated as implied by the iterative-corrections model.

In 1993, Chua and Elliott set out to test the predictions involved with the stochastic optimized submovement model when looking at the nature of visuomotor regulation in aiming movements. The first experiment involved subjects performing aiming movements with full vision of the cursor (VC) and no vision of the cursor (NC). They found visual conditions did influence movement time where the stochastic model predicts movement time should be independent of visual conditions. The stochastic model also predicts movement endpoints to be distributed about the center of the target and that the distribution is independent of visual conditions. Chua and Elliott's (1993) findings concur with this. Subjects did not have a tendency to only overshoot or undershoot the center of the target. Compared to the NC condition, subjects were more consistent in the VC condition. Endpoints did become more variable with the larger targets during the VC condition indicating that subjects were using vision to make use of the larger targets. Subjects, also, reached peak velocity earlier, had a greater number of deviations in the acceleration profiles, and had a greater number of secondary accelerations during the vision condition. A greater number of significant deviations following peak velocity and zero crossings occurred during the vision condition as well. This suggests that a greater number of modifications were made with vision to facilitate a more successful movement. This too contrasts with Meyer et al.'s (1988) paper, in that they found improved performances associated with visual feedback to be independent of the number of movement modifications in the trajectory.

Experiment 2 of Chua and Elliott's 1993 paper involved four conditions, two of which were vision for the first half of the cursor movement (FHV), and vision for the last half of the cursor movement (LHV). Comparing the two conditions it was found that vision on the last half of the movement produced superior performance. In contrast to Meyer et al. (1988), this finding suggests that having vision of the cursor when closing in on the target is the most optimum condition for improved results. Therefore, Chua and Elliott (1993) support the contention that visual information from the latter half of the movement provides the greatest advantage.

Early work by Carlton (1981a) falls in line with Chua and Elliott's 1993 work. He found superior aiming performance resulted when there was vision on the last 25% of the movement. Subjects were required to perform a discrete aiming movement to a target under five visual conditions. These conditions consisted of full vision, 25%, 50%, 75%, or 93% of the initial movement distance unsighted. When up to 50% of the movement amplitude was visually unavailable the movement times were essentially the same. Most importantly, when vision was occluded on the last 25% of the movement a performance decrement occurred with movement times increasing as a larger percent of the movement was performed without vision (Carlton, 1981a). Similar results presented by Temprado, Vielledent, & Proteau (1996), where they looked at aiming performance when there was vision of the hand, vision of the hand during various portions of the movement, and no vision of the hand at any point of the movement. Results, again, supported vision at the end of the movement, other than full vision, ensured optimal performance.

Relationship Between Restrictive and Non-Restrictive Targets

Recent work by Carlton (1994) and Yao and Fischman (1999) looked at the role of spatial boundaries surrounding targets, more specifically restrictive versus non-restrictive targets. Their work suggests that when moving to non-restrictive targets (crosshair with no spatial boundaries) movement times are faster than when aiming to restrictive targets (spatial boundaries). What this finding suggests is that movements to targets without spatial boundaries should result in faster movements. The restrictive targets in their studies were designed by encompassing 95% of the spatial endpoints of movements made to the non-restrictive target. Thus, in all cases, the restrictive target was larger in area than the non-restrictive target.

Both studies involved two conditions: a temporal-accuracy condition and a time minimization condition. Carlton's (1994) study had subjects aiming to a restrictive target under the time-minimization condition and aiming to the non-restrictive target under the temporal-accuracy condition. Carlton (1994) found that discrete aiming movements under time-minimization constraints produced shorter movement times compared to movements made under temporal-accuracy constraints. The results were attributed to the ability of the subject to come close to the target with moderate spatial variability. Once the hand was close to the target, visual feedback could be used for corrections. Note it was found that movements to the restrictive target were faster than to the non-restrictive. This finding can be attributed to the fact that Carlton had subjects aiming to the non-restrictive target under the temporal-accuracy condition where they had a goal time of 400 ms. Movements under time-minimization should have been expected to be faster no matter what target they were aiming to.

Yao and Fischman (1999) performed a similar study, except that both targets, restrictive and non-restrictive, were used under both temporal-accuracy and time minimization constraints. They too found aiming movements made under time-minimization constraints produced faster movements, whether it was to a restrictive or non-restrictive target. Also, movements made as fast as possible to restrictive targets produced slower movement times compared to movements made to non-restrictive targets.

Other significant findings were that for the non-restrictive target under both types of temporal constraints produced the lowest amount of submovements. The authors attributed this finding to the idea that non-restrictive targets have more relaxed spatial boundaries therefore negating the need for secondary corrective submovements. The non-restrictive target in this experiment involved a crosshair. Because of the movement goal and target shape, the crosshairs were less restrictive than the restrictive circle target, and allows a choice of spatial errors[2] (Latash & Gutman, 1994; Yao & Fischman, 1999).

Expanding on the work of Carlton (1994) and Yao and Fischman (1999), Mariuz and Weir (2000) conducted an experiment involving aiming movements to restrictive and non-restrictive targets. The restrictive targets involved three circle targets, which were 24, 12, and 6.2mm in diameter. Non-restrictive targets were a 3mm circle target and a 6.2 mm line target. It was expected that participants would treat the 3mm circle target as a non-restrictive target due to the fact that the aiming cursor was larger in size, 5.9mm in diameter. Latash and Gutman (1994) indicated that a target point is considered to be non-restrictive. Relating this to Mariuz & Weir (2000), having the target smaller than the cursor may represent a lack of spatial boundaries because as the cursor was placed over the target participants cannot visually detect where the target was located underneath. The 6.2mm line target was categorized as non-restrictive because participants were not

[2] A quantifiable target (e.g., circle) "imposes explicit restrictions upon changes in certain variables of the performance, such as final position, movement time, or some others" (Latash & Gutman, 1994, p. 157). When participants are presented with a nonquantifiable target (e.g., a point) there is a choice for permissible errors. Participants may have their own understanding of how accurate/inaccurate they are.

required to aim for the center of the target but to simply land on it, and there were no real boundaries for the cursor.

Participants were required to perform discrete aiming movements under two separate conditions. The first involved moving at a self-paced speed and the second condition involved moving at a fast as possible speed. The purpose of Mariuz and Weir's (2000) study was first to compare movements to a restrictive (6.2mm diameter circle) target and a non-restrictive (6.2mm line) target. It was hypothesized that the line target would produce faster movements. The second purpose was to examine the relationship between cursor size and target size. A cursor (5.9mm diameter) was moved to targets that were smaller than, similar to, or larger than the cursor. A measure of tolerance (target width – cursor width) was calculated for each target/cursor combination. It was hypothesized that a negative tolerance value would result in faster movements because participants would perceive a less restrictive aiming environment as the cursor size exceeds the target size.

Interestingly, the authors found that participants did not differentiate between the restrictive circular target and the non-restrictive line target in either the self-paced or fast-paced conditions. The cursor size may have influenced the line target, as it was similar in size, causing it to be more restricted then what was expected. This suggests that visual feedback about the target in relation to the cursor may affect aiming movements. When comparing the five tolerance conditions, participants did not view the negative tolerance condition as being less restrictive. In fact, the 3mm target resulted in the slowest MT with the greatest amount of deviations after peak velocity in both the self and fast-paced conditions. Thus movements to this target were constrained. Moving to a small target with a large cursor produces the greatest interference in movement execution. It is unclear at this point whether this finding is due to the participants being unable to judge the location of the target beneath the cursor, or to participants slowing their movement to center the cursor over the target. The control parameter accounting for either of these explanations appears to be a lack of vision about the target's spatial boundaries as the greatest number of deviations occurred for the 3mm target and a longer amount of time was spent post peak deceleration.

The results from Mariuz & Weir (2000) pilot work led to an interest in the relationship between cursor size and target size. There have been many studies examining the relationship between target size and amplitude, visual feedback and accuracy, or movement time and accuracy. Most studies involve positioning a cursor/stylus that is always smaller than the target, thus, providing visual feedback about the target once the cursor hits the target region. To date, there has been little research analyzing the target/cursor relationship, where feedback about the target is not available because the cursor is larger than the target. It is this idea that has led to the following study.

As a derivation of this review of literature, the purpose of the present study was to: 1) examine the relationship between the cursor size and the target size in manual aiming and 2) examine the role vision plays in controlling how participants approach targets under various forms of visual feedback.

Methodology

Participants

Participants consisted of seven females ($\overline{x}$ = 20.1 years, SD = 0.68 years) and seven males ($\overline{x}$ = 23.4 years, SD = 2.38 years) two of which were graduate students and the rest undergraduate students. All participants had normal or corrected to normal vision. Before the actual experiment, all participants read an explanation of the study and signed a waiver sheet indicating that they agreed to participate in the present study.

Apparatus and Task

An illustration of the apparatus used is presented in Figure 1. A black wooden box, 63cm X 65cm X 57.5cm was divided by a fully silvered mirror. The mirror was mounted at an angle of 15 degrees, with the anterior edge of the mirror at a height of 22cm from the table surface. A hole in the upper surface of the box corresponded to the dimensions of a 14" (36cm) computer monitor allowing the monitor to be placed in a fully inverted position. The cursor and targets were projected onto the surface of the mirror. A Summa Sketch III graphics tablet sampling at 122.3 Hz (temporal resolution = 8.17ms per frame) was situated inside the box directly beneath the mirror.

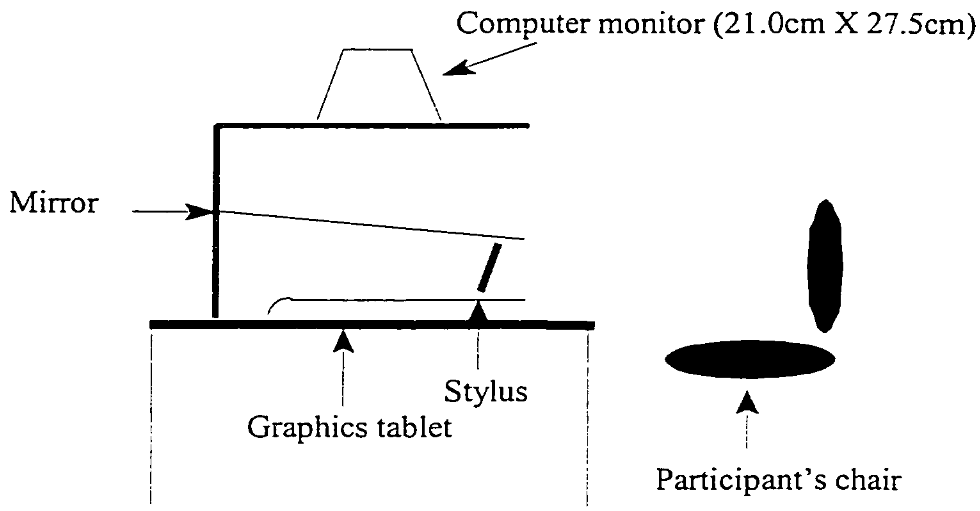


Figure 1: Schematic representation of experimental apparatus.

Participants performed aiming movements on the tablet with a hand-held stylus. Given the experimental set up, the movements were performed in a direct mapping situation, with a one to one proportional correspondence between the cursor movement on the mirror and the stylus[3]. Once the target had been placed in the home position a circular target appeared 12cm directly anterior to the home position. With the appearance of the target, participants started the aiming movement. Target sizes were 3mm, 6mm, 9mm, 12mm, and 21mm in diameter, with the corresponding ID and tolerance (T – C) values shown below in Table 2. There was a constant circular cursor size of 9mm. This

[3] The observed movement on the mirror is 60% of the actual movement on the graphics tablet. The 120mm movement on the tablet is observed to be a 72mm movement on the mirror. A one to one proportional correspondence exists such that when 10% of the movement is completed on the tablet 10% was also observed to be completed on the mirror.

provided targets that were larger than, equal to, and smaller than the cursor (Refer to Table 2).

Table 2. Target index of difficulty and tolerance values.

Target Size	3mm	6mm	9mm	12mm	21mm
ID Values	6.32	5.32	4.74	4.32	3.51
Tolerance Values	-6	-3	0	3	12

Procedure

The experiment took place in a dimly lit room where participants were seated in front of the aiming apparatus with the midline of their body aligned with the black box. The aiming movements were performed in a bottom to top vertical direction, away from the participant. Once the cursor was placed inside the home position the appearance of a circular target initiated the start of the trial. All participants were instructed to move the cursor from the home position to the target region as quickly as possible (for detailed instructions refer to Appendix B). There was no auditory feedback when participants moved the stylus on top of the tablet.

Participants completed aiming movements within two vision conditions. Condition 1, a full vision condition, consisted of aiming a red circle cursor to a blue circle target, where the blue target could be seen through the red cursor. Thus vision was available throughout the whole movement and movement termination. Condition 2, a partial vision condition, consisted of aiming a white circle cursor to a blue circle target where the blue target could not be seen through the white cursor. In this condition there was a lack of visual feedback about the position of the cursor with respect to the target, where targets were smaller than the cursor.

The conditions were blocked in a counterbalanced fashion where half of the participants completed Condition 1 first and the other half completed Condition 2 first. Within each blocked condition the presentation of the target sizes were randomized. During all trials the cursor size and amplitude remained constant. In both conditions, the same size circle targets were presented. Five circle targets were presented with one target the same size as the cursor, two targets larger than the cursor, and two targets smaller than the cursor. The participants moved the stylus as quickly as possible to the target, once the target was reached, participants were required to stop and remain on the target until the target disappeared, and then return to the home position.

Each participant performed five practice trials before performing under each vision condition. The practice consisted of the same task as the experiment except with different size targets. This allowed familiarization with the apparatus and task itself. Once the practice trials were completed, participants then went on to complete a total of 150 trials for both conditions consisting of fifteen trials of each target in a randomized order.

Data Reduction

The raw data collected from all experimental trials were filtered using a second order dual pass Butterworth filter with a cutoff frequency of 7 Hz. The cutoff frequency was determined through a residual analysis as outlined in Winter (1979). Using the primary direction of the movement (y-axis) the instantaneous velocity was calculated by differentiating the displacement data using a three point central finite algorithm. Using the same algorithm, instantaneous acceleration was calculated by differentiating the velocity data. The point in time where instantaneous velocity was equal to or greater than 5.0mm/sec and remained at or above this criterion for at least 72 ms (≅9 Frames) was defined as the beginning of the movement. The end of the movement was defined as the point at which instantaneous velocity fell below 5.0mm/sec, and remained at or below this criterion for at least 72 ms. Movement time (ms) was calculated by determining the number of frames between the defined start and end of the movement and multiplying by 8.17 ms per frame. Time to peak velocity (ms) was determined by identifying the frame in which peak velocity was reached and subtracting this value from the frame defined as the start of the movement, and then multiplying by 8.17 ms. Time after peak velocity (ms) is the difference between total movement time and time to peak velocity.

Data Analysis

An analysis of the acceleration and velocity profiles was performed to determine whether movement modifications to the trajectory occurred. Velocity and acceleration profiles allow observation of these corrections, which include deviations before and after peak velocity. Deviations are reversal points other than peak positive acceleration and peak negative acceleration. The deviations were considered both prior to and after peak velocity and two criteria had to be met: 1) the reversal must have lasted at least 72 ms and 2) the reversal must have reached an amplitude of at least 10% of the greatest absolute magnitude in acceleration (Chua & Elliott, 1993). The 72 ms temporal criterion was chosen as it has been demonstrated that secondary submovements take at least 70ms to complete (Van Donkelaar & Franks, 1991). Significant deviations on the acceleration profile reflect a form of continuous feedback corrections, hence, performed on-line.

All dependent measures were analyzed using the DIGKIN analysis program (Chua & Elliott, 1994). The dependent measures are as follows: movement time (ms), peak velocity (mm/s) (the highest point on the velocity profile), time to peak velocity (ms), time after peak velocity (ms), number of corrections per trial, constant error, and variable error. The mean signed error between the center of the target and the cursor position at the end of the movement was defined as the constant error in both the x and y-axis. Variable error was defined as the within subject standard deviation of the signed errors. Error measures were calculated to determine if spatial accuracy and consistency were affected by the experimental manipulation. All dependent variable values were calculated on a trial-by-trial basis and a mean was obtained for each participant for the two conditions.

Statistical Analysis

Once all the collected data were filtered, a preliminary analysis of the movement time (MT) data was conducted to examine the variability of the data. A bandwidth analysis on the movement time data was performed with no bandwidth (all 15 trials), a one standard deviation (SD) bandwidth, and a two SD bandwidth. This analysis was completed on all 14 participants for each of the five targets in the two vision conditions. The method to calculate the bandwidth was by adding and subtracting the standard deviation from the mean MT for each condition. Outliers, or trials that fell outside this movement time bandwidth were removed for all dependent variables. In the no bandwidth analysis, there were 6 out of the 14 subjects who had conditions exhibiting greater that 30% variability in their movement times. This was calculated as (SD/mean * 100). In some cases the variability reached close to 50%. When the 1 SD bandwidth was used, the variability for all subjects for all conditions was on average 12-15% (range 7-28%). Within a subject the variability was quite consistent. Of the 140 sets [14 subjects x (2 condition x 5 target sizes)], 8 conditions were left with 7-8 trials out of 15. Only one subject had 2 conditions with these reduced trial numbers. Over all subjects there were on average 10 trials left. Fifty of the conditions had 10 or greater trials left of the 15. When the 2 SD bandwidth was used, the variability for all subjects for all conditions was on average 22% (range 10-43%). There was less consistency within a subject. On average, as anticipated statistically, there were 14.4 trials left per condition. There were 7 out of 14 subjects with conditions greater than 30% variability, with 5 subjects hovering close to or over 40%.

With careful deliberation, it was decided to use 1 SD bandwidth to remove extreme outliers. The rationale behind this decision is as follows: 1) it dropped the overall variability by 10-11%, 2) the goal of averaging 10 out of the 15 trials was maintained, 3) it eliminated potential practice effects by removing extreme outlier trials, 4) it maintained variance for all subjects in the 12-15% range, and 5) it maintained a homogenous sample of data to work with.

Once the 1 SD bandwidth was calculated, all dependent variable means were analyzed using a 2 condition (vision/partial vision) X 5 Target size/Tolerance (3mm, 6mm, 9mm, 12mm, 24mm) repeated measures analysis of variance (ANOVA). Statistica 5.1 (StatSoft Inc., 1997) was used to analyze the mean data. Statistical significance was evaluated at p=0.05 and post hoc testing was done with the Tukey HSD test. Planned comparisons were performed on variables that produced significant results to provide more specific tests of the predictions.

Exploratory tests were conducted on tolerance to examine the different calculations of tolerance. Linear regression equations were calculated for the following conditions: ID, tolerance (target – cursor), target + cursor, and $ID=Log_2[2A/(2A/W + Cursor)]$. Regression equations for all four conditions were calculated on a trial-by-trial basis for each subject using the individual trial data from the full vision condition. Regressions were also calculated for the same conditions using the means from each of the five targets.

Predictions

1. In 1999, using a Fitts' paradigm, Bryden & Roy (1999) examined aiming different sized pegs to a constant sized hole. They found that the largest peg produced the slowest movement time because it was the same size as the hole to be placed in. It was therefore believed that the 9mm target in the full vision condition would be the most difficult because its tolerance value is zero and requires the most precision. This would result in the 9mm target having the slowest movement time, the slowest time to peak velocity, and time after peak velocity. Also, there would be more corrective movements made to the 9mm target under this condition.
2. It was predicted that in the full vision condition, where the cursor overlaps the smaller targets, participants might view the cursor as the target. Even though this is still a negative tolerance condition participants have full view of both target and cursor

possibly causing the larger cursor to look as if it has become the target; thereby, decreasing movement time, time to peak velocity, and time after peak velocity.

3. In the partial vision condition where the cursor is larger than the targets, and therefore the targets are hidden by the cursor, it was believed that they would have increased movement times. This is consistent with Mariuz and Weir (2000), where participants treated a target smaller than the cursor as the most difficult resulting in the slowest movement times.[4]
4. In the partial vision condition, it was believed that as targets increased in size from the 9mm target (same size as cursor), movement time would decrease as target size increased. Target tolerance values ranged from zero to positive. This supports a Fitts' effect as found by many studies (Fitts, 1954; Zelaznik et al., 1988; Heath et al, 1998). The same effect was predicted to occur for targets that ranged from 3mm to 9mm under this same condition. As target size increased movement time would decrease. This produces a negative to zero tolerance.
5. It was predicted that for both partial and full vision conditions, as the targets increased in diameter from 9mm to 21mm there would be no difference between vision conditions because the cursor would be seen inside the targets' boundaries. All produce positive tolerances. As both conditions were predicted to produce this result, these trials were considered to be a test of replication.

[4] Yao & Fischman (1999) predict this to be the fastest condition (decreased movement times), as it would be considered a non-restrictive target. However, in their study the cursor was always smaller than the target allowing visual feedback about the target's spatial boundaries.

Results

The results section is organized to examine the influence of vision and target size on: performance measures; the production of movement kinematics; issues of movement correction; and, the target cursor relationship in Fitts' law.

Table 3. Means for all dependent variables for full and partial vision conditions, standard deviations in brackets.

	Full Vision	**Partial Vision**
Movement Time (ms)	713.43	727.24
	(392.76)	(216.67)
Peak Velocity (mm/sec)	489.26	520.97
	(197.81)	(271.49)
Time to PV (ms)	240.60	232.94
	(101.48)	(101.67)
Time after PV (ms)	472.83	494.30
	(116.75)	(143.65)
Deviations before PV	0.53	0.51
	(0.54)	(0.57)
Deviations after PV	0.90	0.87
	(0.60)	(0.62)
Variable Error (mm)	2.52	2.43
	(1.03)	(1.42)
Constant Error (mm)	0.10	0.31
	(1.48)	(1.24)

Performance Measures

Analysis of mean movement time revealed only a main effect for target, $F(4,10) = 1.10$, $p < .05$. There was no main effect for vision, $F(1,13) = .15$, $p > .05$ and no interaction, $F(4,10) = .86$, $p > .05$. Participant's movements to the 21mm target were faster than to the 6, 9 and 12mm targets (see Table 4).

Table 4. Dependent variable means for each target size, * indicates significance.

Size	3mm	6mm	9mm	12mm	21mm
Tolerance	**-6**	**-3**	**0**	**3**	**12**
Movement Time*(ms)	707.74	750.15	732.37	728.22	683.20
	(191.72)	(215.71)	(233.33)	(210.14)	(191.72)
Peak Velocity (mm/sec)	504.18	493.72	508.60	507.59	511.49
	(227.33)	(227.73)	(242.16)	(236.30)	(239.60)
Time to PV (ms)	236.93	240.23	236.87	236.43	233.40
	(98.23)	(106.67)	(104.94)	(103.59)	(188.82)
Time after PV* (ms)	470.81	509.92	495.51	491.79	449.80
	(119.44)	(138.76)	(142.04)	(130.50)	(120.25)
Deviations before PV	0.58	0.51	0.55	0.48	0.48
	(2.41)	(0.54)	(0.62)	(0.51)	(0.53)
Deviations after PV	0.89	0.99	0.92	0.80	0.83
	(0.65)	(0.66)	(0.65)	(0.55)	(0.56)
Constant Error (mm)	0.26	0.59	0.32	0.28	-0.17
	(0.85)	(1.11)	(1.23)	(2.11)	(1.49)
Variable Error* (mm)	2.42	2.41	2.29	2.29	2.97
	(1.28)	(1.29)	(1.42)	(1.11)	(1.04)

Aiming accuracy did not vary as a function of vision, $\underline{F}$ (1,13) = .67, $\underline{p} > .05$, or target size, $\underline{F}$ (4,10) = 1.62, $\underline{p} > .05$ as reflected by the constant error values. On average, constant error values reflected an overshooting of the middle of the target, with the exception of the 21mm target, where a slight undershooting occurred. The data did not provide a significant interaction, $\underline{F}$ (4,10) = .67, $\underline{p} > .05$.

Performance consistency, or variable error revealed only a main effect for target size, $\underline{F}$ (4,10) = 2.98, $\underline{p} < .05$, with no main effect for vision, $\underline{F}$ (1,13) = .18, $\underline{p} > .05$, and no interaction, $\underline{F}$ (4,10) = .50, $\underline{p} > .05$. Participants were less consistent in their movement endpoints when aiming to the 21mm target as compared to the 9 and 12mm targets. For all other targets consistency measures were comparable. Combining measures of accuracy and consistency revealed that aiming accuracy fell within the spatial boundaries for the 6, 9, 12, and 21mm targets. The 3mm target, given its small margin for error had movement endpoints fall outside the boundaries.

Accuracy was a direct function of target size. This is shown by the percentage of endpoints outside the target boundary. The percentages were calculated by taking the mean variable error plus the constant error for each participant for each condition. A percentage of movement endpoints that indicated a target miss based on CE + VE was calculated. In line with Fitts (1954), all participants decreased the number of trials where participants overshot or undershot the target boundaries as target size increased (Refer to Table 5).

Table 5: Percentage of endpoints outside target boundary.

Condition	**3mm**	**6mm**	**9mm**	**12mm**	**21mm**
Full Vision	42%	20%	10%	3%	0%
Partial Vision	41%	10%	5%	4%	0%

Kinematic Measures

Analysis of peak velocity, did not demonstrate a main effect for target size, $\underline{F}$ (4,10) = 1.10, $\underline{p} > .05$, vision, $\underline{F}$ (1,13) = 1.04, $\underline{p} > .05$, or an interaction, $\underline{F}$ (4,10) = 1.86, $\underline{p} > .05$. This indicates that neither the vision condition nor size of the target participants were aiming to influenced their initial impulse. Impulse is often thought to reflect movement planning. Thus, in the current experiment, movement planning was not affected by vision of the cursor at the end of the movement or the size of the target.

These results support Woodworth's (1899) theory concerning two phases of an aiming movement where the first phase, the initial impulse phase, is a non-visually guided ballistic movement. The second phase, called current control, is where vision is used to home in on the target.

Time to peak velocity was analyzed, only to reveal no main effects for target size, $\underline{F}\ (4,10) = .58$, $\underline{p} > .05$, or vision, $\underline{F}\ (1,13) = .72$, $\underline{p} > .05$, and no interaction, $\underline{F}\ (4,10) = 1.49$, $\underline{p} > .05$, thus supporting that the ballistic portion of the movement was programmed the same way for all conditions.

Analysis of time after peak velocity revealed a main effect for target, $\underline{F}\ (4,10) = 3.31$, $\underline{p} < .05$, with no main effect for vision, $\underline{F}\ (1,13) = .42$, $\underline{p} > .05$, or interaction effect, $\underline{F}\ (4,10) = .31$, $\underline{p} > .05$. A post hoc analysis revealed that the time spent in deceleration was significantly different for the 3 and 6mm targets. The time spent in deceleration when moving to the 3 and 21mm target was significantly shorter than the 6, 9, and 12mm targets. Thus, the lengthened MT for these targets was a function of the greater time spent in deceleration.

Movement Corrections

Deviations have been described as re-acceleration points other than peak acceleration and peak negative acceleration, or secondary corrections to the movement, demonstrating a continuous mode of control (Chua & Elliott, 1993). Deviations made prior to peak velocity were analyzed and did not reveal significant effects for target, $\underline{F}\ (4,10) = 3.09$, $\underline{p} > .05$, vision, $\underline{F}\ (1,13) = .16$, $\underline{p} > .05$, or an interaction, $\underline{F}\ (4,10) = .39$, $\underline{p} > .05$. Analysis of deviations made after peak velocity were also analyzed and did not reveal any main effects for target size, $\underline{F}$ (4,10) = 1.38, $\underline{p} > .05$, or vision, $\underline{F}$ (1,13) = .04, $\underline{p} > .05$, and no significant interaction, $\underline{F}$ (4,10) = .99, $\underline{p} > .05$. This lack of significance suggests that participants were not using vision to control the end of the movements, regardless of the target size.

Target – Cursor Relationship Testing

As a test of Fitts' law, regression equations were calculated were using trials for each subject. Significant relationships for 4 of 14 participants were revealed for all analyses: ID, tolerance (T – C), target + cursor, and ID=Log_2[2A/(W + Cursor), and a size effect for tolerance being noted for 5 participants (Refer to Table 6). Tolerance and the target + cursor regressions produced the same R-square value for all participants, whether the regression was significant or not. It was determined that the subtractive nature of Tolerance and the additive nature of target + cursor were the same. Therefore adding or subtracting a constant does not change anything in this case. Analyses using means across participants of the four conditions did not reveal significance for any of the conditions.

Table 6: Significant relationships from participants (N.S. = not significant).

	Condition			
Subject	**ID**	**Tolerance**	**Target + Cursor**	**ID (W=target + Cursor)**
Sub1	N.S.	$R^2 = .04$	N.S.	N.S.
Sub4	$R^2 = .22$	$R^2 = .14$	$R^2 = .14$	$R^2 = .18$
Sub9	$R^2 = .12$	$R^2 = .13$	$R^2 = .13$	$R^2 = .12$
Sub10	$R^2 = .13$	$R^2 = .18$	$R^2 = .18$	$R^2 = .16$
Sub12	$R^2 = .26$	$R^2 = .31$	$R^2 = .31$	$R^2 = .30$

The present study adopted a modified version of Fitts' experimental paradigm where there were conditions that involved movements of a large cursor to smaller targets, thus presenting a negative tolerance. Fitts' (1954) presented an experiment, in some fashion comparable to the current study. He had subjects aiming discs and placing them over a constant sized peg. A hole in center of the discs varied in diameter. A negative tolerance situation could have transpired but Fitts' calculated tolerance by subtracting the aiming apparatus from the peg size, which differs from the majority of studies adopting the idea of tolerance (Drury, 1975;Hoffmann, 1995; Hoffmann & Sheikh, 1992; Mariuz & Weir, 2000). Calculating tolerance according to this method provides only positive tolerance conditions. Thus, only positive tolerance data from the present study can be compared to Fitts' disc transfer task data. Targets involved were the 0, 3, and 12 tolerances, as they were the same size or larger than the cursor.

An analysis of movement time revealed that as target size increased from 9mm to 21mm MT decreased (Refer to Figure 2B). A post hoc test revealed that MT of the

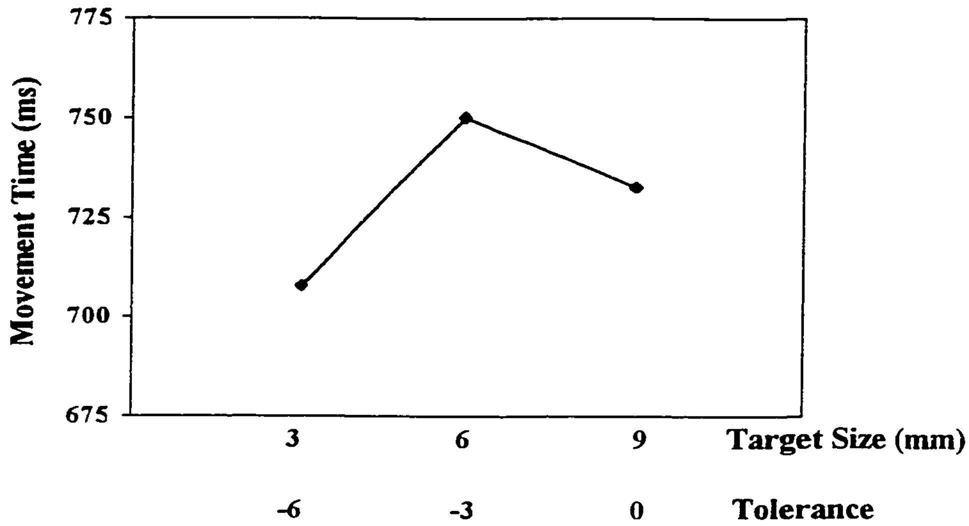
21mm target was significantly shorter than the 6, 9, and 12mm targets (Refer to Table 4). Analysis of movement time in regards to tolerance reveals that as the positive tolerance increases, 0 to 12, MT decreases. This was predicted as these three targets were used by the original method for a Fitts' paradigm (Refer to Table 1). A regression analysis conducted on the 9, 12, and 21mm targets for Index of Difficulty resulted in a r value of 0.96. A regression analysis on tolerance for the positive tolerance targets (9, 12, & 21mm) produced a value of r equal to 0.99. These results indicate that tolerance and ID for the 9, 12, and 21mm targets were highly correlated and both plausible methods for target – cursor analysis.

As Fitts does not allow for a formal analysis of the target – cursor relationship, various tolerance issues must be examined. When comparing tolerance, negative (-6, -3, 0) or positive (0, 3, 12) tolerance relationships can develop[5]. When implementing this method of analysis, it is possible to assume that as tolerance increases in a positive direction movements become easier. The current study found this to be true, as the targets increased in size from 9mm to 21mm, movement time decreased (Refer to Figure 2B). According to the literature the same should occur for negative tolerance conditions (Hoffman, 1995; Hoffmann & Sheikh, 1991). Results of the present study did not support these findings. In fact, the 3mm target produced the fastest MT of the three targets (3, 6, 9mm). Thus, the negative tolerance condition provided a different movement time pattern compared to the positive tolerance conditions (Refer to Figure 2).

When the situation of targets with the same tolerances presents itself, movement time between these targets should be similar. The present study afforded such a situation.

[5] The 9mm target is included in both positive and negative tolerances for demonstrative purposes as it is a zero tolerance and to allow three targets to be analyzed versus only two targets.

A.



B.

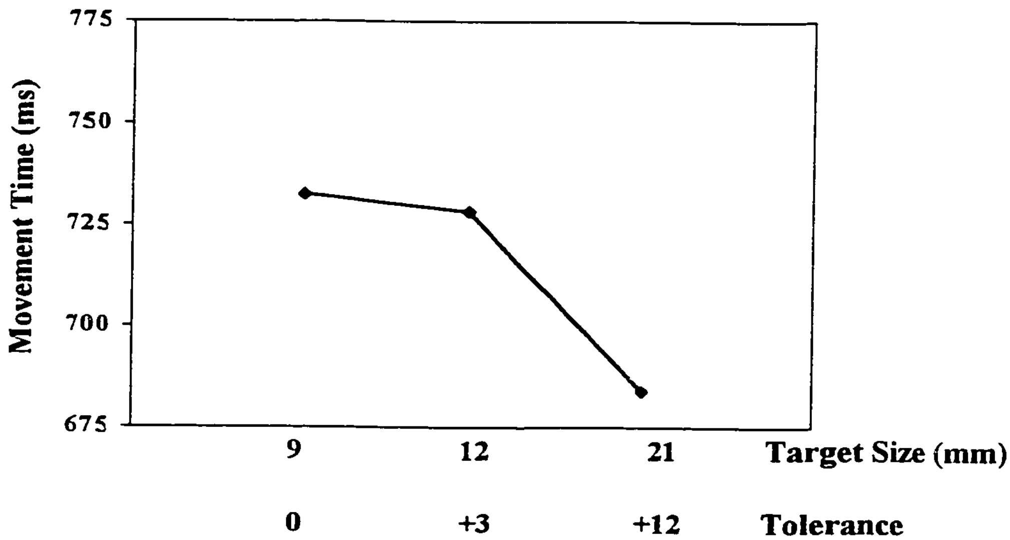


Figure 2: **(A)** Effects of target size (3, 6, & 9mm) and tolerance (-6, -3, & 0) on movement time, collapsed across conditions; and **(B)** Effect of target size (9, 12, & 21mm) and tolerance (0, 3, & 12) on movement time, collapsed across conditions.

The 6mm target and the 12mm target had tolerance values of –3 and 3, respectively. As both had the same level of difficulty, just in different directions, movement times should be statistically similar. Results of a planned comparison (Keppel, 1982) found this to be true, $\underline{F}$ (1,13) = 2.69, $\underline{p}$ > .05, thus indicating that participants approached both targets in a similar manner.

Results of a planned comparison did not reveal a statistical difference between the 3 and 21mm target, $\underline{F}$ (1,13) = 1.71, $\underline{p}$ > .05, although tolerance values for these two targets were –6 and 12 respectively. Other comparisons of targets with different tolerances revealed statistical differences. Participants may have viewed the 3mm target to be an easier target related to the larger size of the cursor, which usually occurs when aiming to large targets with small cursors. Both could be considered to have a larger margin of allowable error around the target.

In regards to specific predictions, all were hypothesized to be based on an interaction, with the exception of prediction 5. Main effects for vision were absent, and there were no interactions between vision conditions and targets. Prediction 5 hypothesized that an interaction due to vision would not occur because it was considered a test of replication. It was stated that for the 9mm to the 21mm targets there would be no difference between either vision conditions, which occurred. Aspects of each prediction are still addressed and discussed.

Discussion

The aim of the present study was to examine the relationship between target size and cursor size and the influence of vision on manual aiming. This was accomplished through an experimental design where participants performed aiming movements with a cursor to five different target sizes with two different conditions of visual feedback at the end of the movement. Performance and kinematic measures, as well as movement corrections and tolerance effects were analyzed to determine how participants controlled their movements under the various conditions in which they were tested.

Many issues are addressed examining possible explanations for the results of the present study. In attempts to answer all theoretical issues the same data may be explained from more than one perspective. While this may seem repetitive and redundant, it is critical for the analysis of all questions and the redundancy is necessary.

Speed-Accuracy Relationship and Target Size Effects

The speed-accuracy relationship demonstrates that as individuals increase movement speed, accuracy is compromised. More specifically, as target size is increased movement time decreases. Generally, the present study found that as target size increased movement time decreased. This result was expected on the basis of the ID of the targets (Fitts, 1954). However, the 3mm target, with the highest ID, did not follow this pattern. The 3mm target had the second fastest movement time next to the 21mm target, thus conflicting with traditional findings. This pattern is also in conflict with the data from Hoffmann's (1995) inverted task. In the present study it appears that the 3mm target became like the cursor. Numerous studies have found that aiming a small cursor to a large target produces fast MT's (see Table 1), as the cursor easily fits into the target. Therefore, when aiming to the 3mm target with the large cursor, participants appear to adopt the same strategy and the target becomes like the cursor. Results of a planned comparison support this explanation in that the 3 and 21mm targets were not statistically different from each other, thus indicating that they were both easier movements and are possibly accomplished by the same movement strategies. The notion that the 3mm target was being viewed as the "cursor" may be similar to Latash and Gutman's (1993) idea regarding restrictive and non-restrictive targets. This idea will be discussed further later in the discussion.

When comparing the current results to various studies that have incorporated similar amplitudes and target sizes, the present study had significantly slower movement times (Carlton, 1994; Yao & Fischman, 1999; Hoffmann, 1995; Hoffmann & Sheikh, 1991). This may have occurred due to the experimental equipment used. Previous studies using the Summa Sketch III graphics tablet have demonstrated a tendency for slower movement times (Elliott, Chua, Pollock, & Lyons, 1995; Heath, Roy, & Weir, 1999) compared to studies using similar target sizes and amplitudes in a 3-D aiming task (Goggin & Meeuwsen, 1992; Hoffmann, 1995; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Spijkers & Spellerberg, 1995). The difference between these two tasks may lie in the fact that when using a stylus or mouse on a graphics tablet, active deceleration of the mouse/stylus is required in order to stop on the desired target location. In contrast, in the more traditional 3-D aiming tasks, passive deceleration of the finger or stylus occurs as it makes contact with the target surface. The difference between active and passive deceleration may account for the lengthened movement time.

A second factor that may account for the lengthened movement time is the difference between participants emphasizing speed versus accuracy in the aiming movement. In 1966, Fitts and Radford addressed this issue and found that aiming movements performed in conditions emphasizing accuracy or speed produced almost identical results. Aiming movements performed in conditions emphasizing accuracy produced accurate results, whereas movements performed when speed was emphasized were faster, however accuracy was maintained. This indicates that despite the instructional set provided participants chose to move accurately. Therefore, the lengthened movement time results in the present study may be attributed to a combination of a tendency for participants to be accurate in their aiming movements and the instructional set. Participants were told (Appendix B) to move as quickly as possible with the instruction to hit the target, thus indirectly emphasizing accuracy.

The present data resulted in a time after peak velocity main effect for target size such that as accuracy demands increased there was a lengthened deceleration phase. This finding is consistent with the existing literature (Carlton, 1981b; Crossman & Goodeve, 1963/1983; Goggin & Meeuwsen, 1992; Heath, Roy, & Weir, 1999; MacKenzie et al., 1987; Soechting, 1984). Again, the 3mm target was the exception. While this condition had a high index of difficulty value it did not have a slow movement time or a long deceleration phase. This is in contrast to Goggin and Meeuwsen (1992) who reported that participants performing aiming movements spent a longer time in deceleration in more difficult conditions. As was previously discussed, the 3 mm was not a difficult condition in comparison to the other target sizes, as participants may have been treating the cursor/target relationship differently.

A lengthened deceleration phase often indicates that movements are being guided on-line by vision, which allows for the reduction of errors in a movement. Interestingly, an analysis of deviations showed that participants made a similar number of corrections in each vision condition. Thus, participants chose to perform accurately rather than with speed, a possible influence of experimental instructions (Fitts & Radford, 1966) and in doing so greatly increased movement times so that error corrections were not required.

In MacKenzie et al.'s (1987) study, aiming movements were performed under conditions where the movements had the same ID values but different amplitudes and target sizes. This was done to determine if participants used "different planning and control processes depending on the combination of amplitude and target size" (pp. 629). They reported target width to be typically responsible for influences on movement time and time after peak velocity. MacKenzie et al. (1987) stated that time after peak velocity was predicted by ID as accurately as movement time was, which could also be said for the present study. Results verified that with an increase in ID, MT decreased, with the exception of the 3mm target. This pattern supports many previous findings (Fitts, 1954, Heath, Roy, & Weir, 1999; Goggin & Meeuwsen, 1992;MacKenzie et al., 1987).

The current study's constant error data suggest that participants were slowing down at the end of their movement to center the cursor over the targets. Past research has demonstrated a tendency to aim for a target's center despite a lack of instruction to do so (Heath et al., 1998). Heath et al. (1998) found that despite the size of target the participants were aiming to, or the presence of a target perturbation, they aimed to the center of the circle. The fast MT result for the 3mm target can again be attributed to the target becoming like the cursor. Such a large difference between the target and cursor constitute an easy aiming condition.

In support of MacKenzie et al. (1987), the present study demonstrated a lack of a significant relationship between time to peak velocity and to target size. With regards to peak velocity, MacKenzie et al. (1987) did report an effect for the magnitude of peak velocity with the largest target having the fastest peak speed. Peak speed then decreased in magnitude as target size decreased. Although in the current study, peak velocity for the 21mm target was faster than all other targets, the 3, 6, 9, and 12mm targets were not significantly different from each other. This is similar to MacKenzie et al. (1987) who reported movements to the largest target were produced with a greater peak speed, while all other targets were not significantly different from each other. In summary, the differences between MacKenzie et al. (1987) and the present study may be attributed to different ID values and a different ID range.

Overall, target size affects how participants produced their aiming movements. Generally, participants followed Fitts' law in that they produced faster movement times as target size increased, with exception of the 3mm target. Plausible reasons to explain why the 3mm target was an anomaly have been presented. Further discussion of control issues surrounding these explanations will be presented later in the general discussion.

Vision

As mentioned previously, there were no significant effects found for vision. This may have resulted due to the limited number of trials where vision was partially occluded. In only three of the possible ten conditions was vision unavailable at movement termination, when the white cursor covered the 3, 6, and 12mm targets. In the present experimental setup, visual feedback was available at the beginning of the movement where movement planning occurs; it was available during movement execution, throughout the actual movement; and up until the cursor covered the target, where terminal vision was occluded for 30% of the trials.

A plethora of experiments examining vision's involvement in successful aiming movements (Carlton, 1981a; Chua & Elliott, 1993; Spijkers & Spellerberg, 1995; Temprado, Vielledent, & Proteau, 1996) have provided evidence as to how aiming movements are controlled under various forms of visual feedback. Such studies have found that vision during the last half of the aiming movement, or vision of the cursor, hand, or target were accurate predictors of movement success. Movement time was optimal during conditions of full vision, however, conditions where vision was available only on the last half of the movement demonstrated results comparable to a full vision condition (Carlton, 1981a, Crossman & Goodeve, 1963/1983; Keele, 1968; Temprado, Vielledent, & Proteau, 1996). Granted, there are different ideas concerning when submovements occur, researchers are in agreement that corrective submovements occur to prevent error in hopes of a successful movement termination (Chua & Elliott, 1993, Meyer et al., 1988). It appears that the participants in the present study adopted a movement strategy that was much more cautious (Goggin & Meeuwsen, 1992, Heath, Roy, & Weir, 1999). Participants decreased movement speed enough to avoid the need for any significant corrections. In congruence with Chua and Elliott (1993) and Heath, Roy, and Weir (1999) participants in the present study spent a longer time in the deceleration phase of the movement. However in contrast with Chua and Elliott (1993), participants in the present study did had a slight tendency to overshoot or undershoot the center of the target, therefore their endpoints were not totally distributed around the center of the target, as the Stochastic Optimized Submovement model predicts (Meyer et al., 1988).

The present data did not provide a visual main effect for variable error, as in Chua & Elliott (1993) and Carlton (1981b). A possible explanation is experimental paradigm differences. As previously mentioned terminal vision was not present for 30% of the trials in the present study, although there was vision throughout the movement and full vision for the other 70%. In contrast, Chua & Elliott (1993) and Carlton (1981a) removed visual feedback throughout various parts of movement execution, such as no visual feedback of the last half of the movement, the first half of the movement, or the first 75% of the movement. Carlton (1981b) examined aiming movements with various forms of visual feedback, vision of stylus, vision of hand, vision of stylus and target, vision of target, full vision, and no vision. Vision of the stylus and target resulted in an outcome comparable to that of the full vision condition. These results emphasize the importance of vision of the target, which occurred for 70% of the trials in the present study. Thus, occlusion of terminal vision, especially for only 30% of the trials, does not provide enough insight to understand the role vision plays in aiming movements presented in the current study. When comparing the present study to past research where large portions of movements are occluded, it seems that experimental design is a possible explanation for the result of no vision effects.

Tolerance

The description of tolerance indicates that tolerance can be viewed as either a positive or negative value or an absolute value. In the present study, participants behaved similarly in the –6 and +12 tolerance conditions (Refer to Table 2 for corresponding target sizes). A negative tolerance, is often considered to be a more difficult condition (Mariuz & Weir, 2000), however, the –6 tolerance condition in the present study had a very fast MT in comparison to some of the positive tolerance conditions (Refer to Table 4). Thus, the negative tolerance condition did not support Fitts' law. In contrast, positive, 0 to +12, tolerance conditions supported a Fitts' effect as MT decreased as tolerance increased (Refer to Figure 2A). In general, the current data show that as the tolerance becomes more positive, or more negative, movement time decreases. This is in contrast to Hoffman (1995) who showed that movement time is dependent on target size and not tolerance as MT decreases as target size increases, and MT increases as tolerance becomes more negative (Refer to Table 7).

A recalculation of Fitts' tolerance values to match the current definition shows a pattern of movement time data similar to the present study (Refer to Table 8). Generally, as the tolerance becomes more negative, movement time decreases. The current data appears to support a relationship between negative and positive tolerance, in that the negative tolerance did not produce the same pattern as in Hoffmann (1995) or Hoffmann and Sheikh (1992). The results do not simply demonstrate a decrease in MT as target size increases; there is also a decrease in MT as tolerance becomes more negative, when comparing the 0 to -6 tolerance conditions (Refer to Figure 2B and Table 7).

The negative tolerance data provides potential insight into understanding the relationship between the target and cursor in manual aiming. These results support Latash and Gutman (1993) where they indicated that movements to a point target are non-restrictive and therefore produce faster movement times. A negative tolerance condition can produce fast aiming movements when the aiming apparatus is perceived to be significantly larger than the target. According to Latash and Gutman (1993), if a target is perceived to be a point relative to the aiming apparatus movements to such target should appear to be less difficult. The 3mm target may have been perceived by participants to be similar to a point and therefore non-restrictive (Carlton, 1994; Latash & Gutman, 1993; Yao & Fischman, 1999), thus explaining the faster MT.

Table 7: Data from three studies implementing tolerance.

Fitts (1954) Exp.2				**Hoffmann (1995)**				**Current Data**			
Hole size (in.)	**Peg Size (in.)**	**Tol. (Hole-Peg)**	**MT (sec)**	**Probe (mm)**	**Target Size (mm)**	**Tol.**	**MT (ms)**	**Cursor (mm)**	**Target Size (mm)**	**Tol.**	**MT (ms)**
.625	.125	.5	.724	15	10	-5	364	9	3	-6	707.74
.375	.125	.25	.771	15	25	10	294		6	-3	750.15
.25	.125	.125	.844						9	0	732.37
.1875	.125	.0625	.896						12	3	728.22
									21	12	683.20

Comparing the three studies in Table 7, it is considered that the Fitts task and the current task required accuracy, whereas in Hoffmann's task accuracy was not as strict. Fitts' task is a very accurate task. Either the disc was on the peg to be successful or it was not on the peg to be a failure. Participants in the current study stressed accuracy, as demonstrated by the slower movement times and an even distribution around the center of the targets. In contrast, Hoffmann (1995) may have allowed a 10% error rate, however subjects practiced the task until they were satisfied they could perform without error. Hoffmann also defined the target area as the target plus the probe, as he adopted the effective target tolerance for analysis of his inverted aiming task. This larger margin of error is similar to Schmidt et al. (1979), where they allowed subjects to hit any part of the target therefore producing an effective target width, thus the target could be defined as the target plus the aiming apparatus. Although, in the present study, participants had error in their aiming, it was approximately 2.5mm (CE + VE), whereas Hoffmann (1995) had 10 and 25mm allowances for error.

Table 8: Fitts' tolerance values calculated according to the current study's definition of tolerance and compared to the current study's data.

Fitts (1954) Exp.2				**Current Data**			
Hole size (in.)	**Peg size (in.)**	**Tol. (Peg - Hole)**	**MT (ms)**	**Cursor (mm)**	**Target Size (mm)**	**Tol.**	**MT (ms)**
.625	.125	-.5	.724	9	3	-6	707.74
.375	.125	-.25	.771		6	-3	750.15
.25	.125	-.125	.844		9	0	732.37
.1875	.125	-.0625	.896		12	3	728.22
					21	12	683.20

General Discussion

Although all predictions were based on interactions and none were found, each prediction must be addressed. Prediction 1 hypothesized that the 9mm target would be the most difficult target in the full vision condition. As already indicated, there were no vision effects. This is thought to have occurred due to the experimental design. For this task, occlusion of the terminal portion of the movement did not affect how participants move. Other studies, which demonstrate vision effects, involved more conditions where larger portions of the movement were occluded (Carlton, 1981a; Chua & Elliott, 1993;

Temprado, Vielledent, & Proteau, 1996). In regards to prediction 2, without incorporating the vision condition, it was supported by the data. The 3mm target did have a very fast movement time compared to the other negative tolerance targets, indicating that the cursor appeared to become like the target. Participants approached this target in a similar fashion as the large targets.

Prediction 3 stated that in the partial vision condition, negative tolerance targets would have an increased movement time as previously demonstrated by Mariuz & Weir (2000). Surprisingly, the 3mm target produced a very fast movement time, especially in comparison to the MT produced by participants in Mariuz & Weir (2000) when aiming to the same size target. This result is attributed to experimental differences. Mariuz & Weir (2000) had participants aiming to a 3mm target with a 5.9mm cursor. Participants may have had difficulty determining the difference between the target and cursor. However, the cursor in the current study was three times lager than the target allowing the participants a large enough difference to detect.

Despite the vision condition, as targets increased from 9mm, movement time decreased as hypothesized in prediction 4. This was also hypothesized to occur for target increasing in size from 3mm to 9mm in support of Hoffmann (1995). This did not occur. The 3mm target produced the second fastest time overall. Thus indicating that a negative tolerance condition is comparable to a positive tolerance condition.

Finally, prediction 5 was supported by the results. It was hypothesized that despite a partial or full vision condition the positive tolerance conditions would be a test of replication, which is what resulted. No interaction was produced, indicating that both vision conditions for these three targets were replicated.

With respect to issues pertaining to movement control, it appears that the current data reflect aspects of both movement programming and on-line, concurrent control of the movement (Woodworth, 1899). Participants preprogrammed the initial portion of the aiming movements, as predicted by Woodworth (1899). The initial approaches to all targets were controlled ballistically. This was shown in the peak velocity and time to peak velocity data. The data was not significant, indicating no difference between the early portions of the movement, no matter what size of target participants were aiming to. This finding may be attributed to the fact that vision was available during the planning stage at the beginning of the movement.

It is believed that on-line visual control was used throughout the concurrent control phase, again as predicted by Woodworth (1899). In the partial vision condition participants were allowed full vision of the movement up until the cursor contacted and covered the target, thereby occluding vision at movement termination. This occurred for only 30% of the trials, allowing concurrent control for 70% of the trials where full vision for the entire movement was available. Given the small number of trials for which terminal vision was occluded, it is not surprising that the two vision conditions in the present study were not different. The error and correction data provide evidence that vision was utilized to reduce errors. Thus when vision is present throughout the movement, on-line visual control of the movement is possible, which results in fewer errors being produced and fewer movement corrections being required. Past studies have experimentally prevented on-line visual control of a movement by occluding vision throughout the concurrent control phase of the movement (Carlton, 1981a; Chua & Elliott, 1993; Temprado, Vielledent & Proteau, 1996). These studies demonstrated that vision of the last 25% of the movement improved movement success, which falls during the concurrent control phase.

In the current study, time after peak velocity reflects a target size effect rather than an error correction effect. Participants used a different timing pattern during the final stages of the movement in relation to the size of the target being aimed to (Carlton, 1980; Heath, Roy & Weir, 1999; MacKenzie et al., 1987), and did not demonstrate any differences in aiming accuracy.

With respect to issues surrounding tolerance, it appears that a relationship between the target and the cursor does exist, and it may be more important than previously realized. According to the current study's data, participants were taking this relationship into account. A feasible explanation for both tolerance and ID producing similar correlation values might be that both relied on the target size. In the case of ID only the size of the target being aimed to is considered in the calculation, while for tolerance it is both the aiming cursor and target that are considered. In relation to negative versus positive tolerances, participants seem to detect a difference. According to the present study's data participants do not simply decrease MT as tolerance progresses from a negative to a positive value, as found by Hoffmann (1995) and Hoffmann and Sheikh (1991). The present study found that, generally, as the difference between target and cursor size increased, in either a positive or negative tolerance direction, movement time decreased (Refer to Figure 2A & Figure 2B). This demonstrates that the size of the cursor affected how participants moved to a target. A recalculation of Fitts' tolerance values, using the current definition of tolerance, resulted in a similar MT pattern found in the current study. This is an important result as it further supports the existence of a relationship between the target and cursor. The recalculation also provided negative tolerance values where the former calculation did not.

The current data and the recalculated Fitts' data demonstrated that the greater the difference between the target and cursor the easier the movement. Such a statement may be misleading as it may indicate that a negative or positive tolerance condition is not important, and rather only the difference between the target and cursor should be considered. However, both issues, the target – cursor difference and the negative and positive tolerance condition, need to be addressed. The negative aspect of tolerance is necessary as this condition is not identical to a positive tolerance condition. The current data, for example, indicated that negative tolerance conditions produced a greater number of endpoints outside the target boundaries (Table 5). This may be attributed to the fact that the cursor was much larger than the targets, especially the –6 tolerance condition, and the participants were unable to be as accurate as they would be if the target was larger than the cursor. This may be due to the fact that the cursor occludes the target, making endpoint accuracy more difficult.

Some of the current results were attributed to methodological differences in comparison to other manual aiming studies. A similar experiment may be conducted using the more traditional 3-D experimental equipment instead of the 2-D equipment that was used. As indicated earlier, movements on the graphics tablet were quite slow. If the same movements were analyzed in a 3-D aiming task, participants may have the freedom to move at a faster speed. Facilitating a faster movement may impact how participants move to presented targets. As mentioned above, incorporating different conditions of visual occlusion may be another mode to overcome methodological differences and bring the experimental design in-line with similar studies.

The current study has provided the "ground" work for future studies examining the relationship between the target and cursor. Suggestions for future research to address this relationship would be to examine aiming movements using different size cursors as well as different size targets. It would be recommended to occlude vision throughout various portions of the aiming movements, not only terminal vision. An examination of eye, head and hand movement patterns may also provide further insights into the target – cursor relationship. Conducting studies examining these experimental conditions may help to improve how researchers address tolerance issues. Possible results may lead to more specific and refined ideas to this relationship. Not until a greater understanding of this relationship exists will there be an agreement on a specific definition of tolerance.

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Appendix A

Glossary of Terms

GLOSSARY

Acceleration: Rate of change of velocity

Amplitude: Distance between the center of the home position and the center of the target

Constant Error (CE): A performance measure. It indicates how close on average the movements come to the target, therefore a measure of accuracy. This measure enables the quantification of the systematic biases that the movements have relative to their spatial goals.

Deviations: Re-accelerations and decelerations that do not include peak positive acceleration and peak negative acceleration.

Index of Difficulty (ID): Calculated by the equation $Log_2(2A/W)$. Therefore, the value is related to how "difficult" the particular combination of A and W was for the subject. The difficulty of a movement is jointly related to the distance that the limb moves as well as to the width of the target being aimed to. The difficulty is measured in bits based on the information theory.

Kinesthetic Feedback: The conscious awareness of the position of body parts and the amount and rate of joint movement.

Movement Time: Is the duration of the time interval from when a movement begins to when it ends.

$\overline{MT} = a + b[Log_2\,(2A/W)]$ where:

- $\overline{MT}$ is the average movement time for a series of taps. It is calculated as the trial duration divided by the number of taps completed during that that time. The equation determines how much time was required for each movement.

- a is the y-axis intercept

- b is the slope

- $Log_2(2A/W)$ is the Index of Difficulty (ID)

Peak Velocity: The highest positive point on the velocity curve, representing the point at which participants move the fastest.

Perturbation: An unexpected physical event that changes the movement or the movement goal.

Primary Submovement: The first movement of the hand moving towards the target, as identified on the acceleration profile.

Secondary Submovement(s): The second and any subsequent movements made towards the target, usually in the form of corrections, as identified on the acceleration profile.

Stylus: A hand held pen-like apparatus, used to make aiming movements on the Summa Sketch III graphics tablet

Terminal Vision: Vision unavailable at the end of the movement as the cursor covers the target.

Time After Peak Velocity: The time from peak velocity to the end of the movement.

Time to Peak Velocity: The time from movement initiation to peak velocity.

Tolerance: The relationship between the target and cursor. It is calculated by the following equation:

$$\text{Tolerance} = \text{Target} - \text{Cursor}$$

The resulting value determines the difficulty of the aiming movement, the smaller the value the more difficult the movement.

Variable Error (VE): A performance measure that reflects consistency. This measure enables researchers to assess the spread of scores around a subject's CE value in a distribution of repeated movements. The greater the noise the greater the VE will be.

Velocity: Rate of change of displacement (or position), where displacement is the term used to describe the straight line that connects a point's position from one instant in time to another.

Visual Feedback: Information gathered by the visual system about the body in relation to the environment.

Zero Crossings: Negative to positive transitions in acceleration following peak velocity (Chua & Elliott, 1993).

Appendix B

Participant Instructions

Instructions:

1. Holding the stylus lightly, position the cursor inside the home position which appears at the bottom of the screen
2. Remain inside the home position until a target appears on the screen.
3. Once a target appears move in one fluid motion as fast as possible to the target.
4. Once you hit the target stop, remain on the target without moving until everything on the screen disappears.
5. Return to the home position and repeat.
6. Any questions concerning the instructions?

VITA AUCTORIS

Jennifer Mariuz was born and raised in Ottawa, Ontario. She graduated from Brookfield High School in June of 1995. September of 1995, she attended the University of Windsor where she obtained a Bachelors of Human Kinetics in Movement Science in 1999. She is currently a candidate for the Master's Degree in Human Kinetics at the University of Windsor and hopes to graduate in spring of 2001.